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COSMIC RAY COLLISIONS IN SPACE

PART IV — COSMIC RAY HAZARDS IN THE SOLAR SYSTEM

by S. N. Milford

Prepared under Contract No. NASw-699 *by*
GRUMMAN AIRCRAFT ENGINEERING CORPORATION
Bethpage, N. Y.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1965

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FOREWORD

This document comprises Part IV of the final report on Contract No. NASw-699, Cosmic Ray Collisions in Space. The complete report describes in detail the research carried out on this contract by the Geo-Astrophysics Section of the Research Department of Grumman Aircraft Engineering Corporation between July 3, 1963 and November 3, 1964. This work was performed under the technical cognizance of Drs. L. J. Cahill, J. W. Freeman, and A. W. Schardt of the Office of Space Sciences, NASA.

The final report is presented in four separately-bound parts:

Part I - The Energy Spectra of Electrons from Pion-Muon-Electron Decays in Interstellar Space;

Part II - High Energy Gamma Rays from Cosmic Ray Collisions in Space;

Part III - Low Energy Protons from Cosmic Ray Collisions in Space;

Part IV - Cosmic Ray Hazards in the Solar System.

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1. Introduction

In recent years, satellite, space probe and balloon flights have given direct measures of the galactic cosmic ray intensity outside the earth's atmosphere, and in some cases outside the geomagnetic field. These and earlier measurements indicate that low and medium energy galactic cosmic rays are partially kept out of the inner solar system by interplanetary magnetic fields. The larger fields at times of solar maximum activity lead to corresponding lower cosmic ray intensities in the inner regions of the solar system, and it is found that an 11 year cycle exists for these cosmic ray intensities. Superimposed on the 11 year solar cycle are a number of irregular variations, such as Forbush decreases, which are presumably due to transient increases in the interplanetary magnetic field.

Ideally, we would like to know the cosmic ray intensity J as a function of the type of particle i, the energy E (or rigidity R), the position in space r (relative to sun or earth), the time t, and the direction of the cosmic ray particles — so that J is a vector:

$$\underline{J}(i, E, \underline{r}, t) .$$

At some future date we can expect to have exact information about interstellar cosmic rays near the solar system, and about the interplanetary (and terrestrial) magnetic fields as functions of time and position in the solar system. Then these can be fed into a diffusion program in a computer; the product will be the cosmic ray spectrum as a function of time and position in the solar system. Since at present we have the necessary information only for very high energy cosmic rays, and to some extent the terrestrial magnetic field, we shall have to be satisfied with a more fragmentary approach. (It is also possible that in future it may be easier to measure the cosmic rays directly than to calculate their intensity!)

Thus, the topics to be covered in this paper are the direct measurements of cosmic ray energy and charge spectra near the earth in Section 2, and in interplanetary space near the earth in Section 3, followed by a discussion in Section 4 of the theory of the effects of planetary magnetic fields and atmospheres in modifying these spectra, and of the interaction of cosmic rays with the moon's surface. In Section 5 we discuss the intensity of interplanetary cosmic rays in the outer solar system, partly using simple models of the interplanetary magnetic fields to give the resulting modulation of low energy interstellar cosmic rays as a function of distance from the sun. The radiation doses will be estimated for the various regions in Section 6.

2. Cosmic Rays Near the Earth

We consider two regions: a) underground, sea level and altitudes within the earth's atmosphere, b) outside the earth's atmosphere but within the geomagnetic field.

Within the Earth's Atmosphere

Measurements under a) have provided vast quantities of information about cosmic rays with energies above about one BeV. Despite the geomagnetic field, very low energy protons can penetrate to the top of the atmosphere near the geomagnetic poles; on the other hand, since the atmosphere has a depth of 1000 gm cm^{-2}, protons with energies of several hundred MeV do not penetrate more than part way through the atmosphere. Since a great part of our information about cosmic rays comes from measurements in the atmosphere, we shall first summarize the information about the nature of primary cosmic rays obtained in this way, because much of it is directly applicable to the space environment itself.

The average cosmic ray particle has a kinetic energy T of some few BeV; at higher energies, which are relatively unaffected by interplanetary magnetic fields, the integral spectrum in terms of the total energy $E = T + 0.94$ (BeV) is given by[1]

$$J(> E) \approx \frac{0.2}{E^{1.5}} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} , \qquad E \gtrsim 10 \text{ BeV} \tag{1}$$

This holds approximately up to energies of $\sim 10^{18}$ eV, and particles with energies up to 10^{20} eV have now been detected by extensive air shower measurements.[2] The omnidirectional total intensity is $\sim 3 \text{ cm}^{-2} \text{ sec}^{-1}$, for $E > \sim 1.5$ BeV.

The primary cosmic rays probably consist of $\sim$ 85% protons, $\sim$ 10-15% helium nuclei, $\sim$ 1% nuclei with nuclear charge $Z \geq 3$, and $\sim$ 3% electrons;[3] other constituents expected to be present with small intensities include the other stable particles: positrons, antiprotons, various neutrinos, as well as gamma rays.[4,44] In recent years emulsions have been exposed to cosmic rays at balloon altitudes with only 2-3 gm/cm^2 of atmosphere remaining above them, so that the corrections for fragmentation of heavy nuclei by the atmosphere before reaching the emulsion are very small. Thus, considerable confidence can be placed in these emulsion measurements of cosmic rays with $Z \geq 2$. The relative abundances of cosmic ray nuclei with $3 \leq Z \leq 11$ determined by Shapiro, et al.[5] are given in Fig. 1, and for $10 \leq Z \leq 28$ determined by Neelakantan and Shukla[6] in Fig. 2; since there appears to be practically no component with $Z > 28$, the sum of the contributions from $3 \leq Z \leq 28$ is the $\sim$ 1% of the primary flux quoted above. There is some uncertainty about whether the energy spectra of all the components have the same shape;[6,7] the measurements of

Koshiba, et al.[7] presented in Fig. 3 suggest that the light nuclei Li Be B are relatively more abundant at lower energies.

The other important properties of primary cosmic rays are that they appear to be substantially isotropic in direction and constant in time, except for modulation by variable interplanetary magnetic fields (see Section 5).

<u>Outside Atmosphere but Within Geomagnetic Field</u>

In this region we consider the primary cosmic rays as modulated by the geomagnetic field, and the secondary ("albedo") particles arising from the interaction of cosmic ray primaries with the earth's atmosphere, or with the earth itself — in this category would be high energy muons produced in the earth's crust by cosmic ray neutrinos coming right through the earth from the opposite side — the expected muon fluxes,[8] however, are too small to concern us here.

The main features of the geomagnetic field shielding of the earth from high energy charged particles were explained many years ago in terms of a simple terrestrial magnetic dipole field, and more recently in terms of spherical harmonic expansions (including higher multipole terms) fitted to the exact measured magnetic fields over the earth's surface (see, for example, Sauer).[9] The simplest effect of the field is to produce a cut-off at a given magnetic latitude of cosmic rays with magnetic rigidity less than a definite value. Here, the magnetic rigidity has its usual definition of momentum to charge ratio: $R = pc/e$, where p, e are particle momentum, charge respectively, and the total energy $E = (R^2e^2 + M^2c^4)^{1/2}$. It has been found, however, by balloon, rocket, and satellite observations, that the geomagnetic cut-offs are not explained accurately by such ground level fields alone. Akasofu, et al.[10] have found that the observed steady and magnetic storm cut-offs can be explained by combining the observed finite extension of the geomagnetic field (the "geomagnetic cavity" in the solar wind), and a physically reasonable ring current at several earth radii (cf. Heppner, et al.[11] and Webber[12]).

More directly, we now have extensive cosmic ray measurements within the geomagnetic field as a function of latitude, longitude, altitude, and also limited periods of time. In the most extensive measurements to date, Lin, Venkatesan and Van Allen[13] used a shielded Geiger tube on Explorer 7 to measure the cosmic ray intensity above 30 MeV during the period October 1959 — February 1961, at altitudes of 550-1100 km. There was a sharp rise in counting rate whenever the satellite entered the radiation belts of the earth, but it was possible to discriminate against the belt radiation by comparing the counts from the shielded Geiger tube and another unshielded one. The resulting intensity is then the sum of the primary cosmic rays and any charged particle secondaries produced in the atmosphere. In this work, as in much of the recent geomagnetic region research, Lin, et al. used the McIlwain[14] magnetic shell parameter L, defined approximately as the equatorial radius (measured in earth radii) of the line of force on which a particular particle is mirroring; Stone[15] has refined the original definition of L. Lin, et al.[13] found (Fig. 4) that the charged particle intensity increases monotonically with increasing L and is accurately constant within experimental error for $L > 2.9$, and that the omnidirectional intensity is $J_0 = 2.0\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ at all high latitudes and decreases to $0.56\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ at the equator. They find also that the charged particle contribution from the upward moving (splash) albedo intensity J_{AS}, and from the re-entrant albedo J_{AR} from reactions in the atmosphere on the opposite side of the earth (see, e.g., Ray[16]), is comparable to that from the primaries J_P. Thus, by using an earlier value for the interplanetary J_{IP}, and the fact that for large L their Explorer 7 measurements covered 70% of the total solid angle:

$$J_0 = J_P + J_{AS} + J_{AR} \quad , \quad J_P = 0.7\ J_{IP},\ J_{IP} = 1.8\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1} \tag{2}$$

they derived the total albedo contribution:

$$J_{AS} + J_{AR} = 0.74\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1} = 0.59\ J_P\ . \tag{3}$$

An important (but indirectly estimated) result was that during this period the primary spectrum had less than 3% of its total intensity in the rigidity range $R < 2.2$ BV (units of billion volts), i.e., proton $T = 1.46$ BeV. Since the cut-off for protons at high L is down to an energy of some tens of MeV, it is probable that this result can be taken over to the interplanetary case near the earth:

$$J_{IP}(T > 1.46 \text{ BeV}) > 0.97\, J_{IP} \,. \tag{4}$$

Of course, as far as radiation hazards near the earth are concerned, it is the total intensity J_0 of Eq. (2) which is important, but for predicting the radiation near other planets (see Section 4) it is important to distinguish the primary (J_P) and albedo (J_{AS}, J_{AR}) contributions.

The other major component of the near-earth radiation is the neutron flux, which derives entirely from reactions of the primaries with the atmosphere. Since the primary spectrum, atmospheric composition, and density are known moderately well, it is possible to calculate the expected neutron flux. Lingenfelter's calculations[17] of the albedo neutron spectrum at several geomagnetic latitudes, for both solar maximum and solar minimum, are presented in Fig. 5. The earlier results of Hess, et al.[18] in Fig. 6, for the neutron spectrum at different distances from the earth, but all at the geomagnetic equator, show the expected decrease in neutron intensity as the distance increases to several earth radii. They note that thermal neutrons with energies less than 0.66 eV will be trapped in the earth's gravitational field and that many will decay in orbit before they return to earth - see Fig. 7.

The recent experimental measurements[19-22] of the neutron flux above the atmosphere differ by a factor of three among themselves. The detectors used give integrated spectra over many decades of energy, so that it is possible to approximate the neutron spectrum very crudely only. Also, part of the results of each Atlas flight were not useful because of the large background due to secondary neutrons produced in the rocket and payload by the protons in the radiation belt. Thus, while at present the experiments are consistent with the calculations of the shape and magnitude of the albedo neutron spectrum to within the experimental differences, more measurements are necessary to check the validity of the theory.

3. Cosmic Ray Measurements in the Inner Solar System

Recent cosmic ray measurements near the orbits of Earth and Venus are discussed — the earlier Pioneer 5 (1960), etc., results are not considered here.

Measurements were made by Mariner B over a path of 360 million kilometers between the orbits of Earth and Venus, and over a period of some 130 days (August 27, 1962 - January 3, 1963). The data available to date[23] indicate an average interplanetary cosmic ray intensity of $3\ cm^{-2}\ sec^{-1}$.

The Explorer 12 and 14 cosmic ray data are also only partly available at present. Explorer 12 had an apogee of 80,000 km on the day side of the earth and was outside the geomagnetic field for more than half the time in each orbit,[24] during which time it measured the interplanetary value of the cosmic rays over a 120 day period beginning August 16, 1961. Since the cosmic rays above 600 MeV produce many secondaries by nuclear interactions in the spacecraft and the detectors, large corrections had to be made by Bryant, et al.[24] to find the low energy differential spectrum given in Fig. 8; there is good agreement with the high geomagnetic latitude balloon results of Vogt[25] from the period August-September 1960 and Meyer and Vogt[26] July-August 1961. However, in comparison with the Lin, et al.[13] measurements, which ended only some 6 months earlier, their results indicate considerably more low rigidity cosmic rays. It is possible[26] that the particles with $T < 200$ MeV are of solar origin. The integral intensity found on 18 August 1961 by Bryant, et al.[24] was $J_{IP}(> 600 \text{ MeV}) = 1.7 \text{ cm}^{-2} \text{ sec}^{-1}$.

4. Cosmic Rays and Secondaries Near Moon and Planets

Since present evidence supports an essentially isotropic flux of interplanetary cosmic rays, the intensity incident on the moon's surface will be just half the free space omnidirectional intensity. The primaries interact with the lunar surface to produce secondary neutrons,[27] protons,[28] alpha particles,[28] pions, muons,[29] electrons,[28] gamma rays,[28,30,44] etc. From the point of view of scientific information, all these should be measured — one recent suggestion[29] is that it might be possible to infer the density inside a lunar mountain by measuring secondary muons of energies 10^3-10^5 BeV traversing the mountain. From the point of view of radiation hazards, only the neutron and gamma ray intensities appear to be significant.

Lingenfelter, Canfield, and Hess[27] calculated the neutron leakage (or albedo) spectrum at the lunar surface, and found that the neutron intensity depended strongly on the chemical composition (particularly the relative hydrogen abundance) — see Fig. 9. The total neutron flux is of the order of $10\ cm^{-2}\ sec^{-1}$.

The gamma ray flux from the lunar surface is estimated by Hayakawa[28] to be $\sim 0.5\ cm^{-2}\ sec^{-1}\ ster^{-1}$ (1-2 MeV), and $\sim 0.03\ cm^{-2}\ sec^{-1}\ ster^{-1}$ ($\sim$ 100 MeV).

In the case of the planets, we can draw upon the extensive measurements and theory for the earth. Obviously, planetary magnetic fields will modulate the interplanetary cosmic ray flux before it reaches the planetary atmosphere. At present, the only direct planetary magnetic field measurements we have are the Mariner B results[23] indicating that the Venusian magnetic field on its sunward side does not extend out to a distance of 40,000 km from the center of Venus; the magnetic field is therefore probably weaker than the Earth's — this is consistent with a slow rotation rate such as is suggested by other observations.

The albedo neutrons and gamma rays emerging from the planetary atmosphere can be calculated as for the terrestrial and lunar cases (see Section 2 and above). Here, we consider the passage of the cosmic rays and their secondaries down through the atmosphere. In the case of Mars, the atmosphere is considerably thinner than the Earth's, so that the cosmic ray secondaries might possibly be a hazard to manned surface activities. If it is assumed that the nuclear composition of the Mars atmosphere has approximately the same neutron/proton ratio as the Earth's atmosphere (which will be the case if the Martian atmosphere is predominantly nitrogen, as currently believed), it is possible to take over, in an approximate fashion, many of the calculations[17,31,32] and measurements[33,34] made for the terrestrial atmosphere. As an example of some of the terrestrial information available, we present in Fig. 10 Lingenfelter's[17] recent calculations of the neutron production rate in the terrestrial atmosphere at solar minimum, using a multigroup diffusion machine program to find the rate as a function of geomagnetic latitude and epoch of the solar cycle.

Yagoda,[35] and Fink and Milford,[36] have used the terrestrial information to estimate the neutron flux at various depths in the Martian atmosphere on the assumption that Mars does not have a large magnetic field. The approximate neutron, proton, muon and electron fluxes given by Fink and Milford[36] are shown in Fig. 11. Yagoda[35] has also pointed out that the rate of "star" production in nuclear emulsions at the surface of Mars would be some orders of magnitude larger than that at the Earth's surface.[37]

As far as radiation near other objects in the solar system is concerned, for those with little or no atmosphere (Mercury, Pluto, all satellites except Saturn's Titan, asteroids), the high energy cosmic radiation at the surface will be comparable with that at the Moon, but the low energy cosmic radiation is expected to have a larger intensity for the outer planets (see Section 5). Thus, the total primary and secondary radiation will be larger than in the lunar case. For those objects with appreciable atmospheres (remaining 7 planets, Titan), most of the atmospheres are probably so thick that the radiation at their surfaces produced by cosmic radiation is expected to be less than that at the surface of the earth (this would not be true for Titan), so that no radiation hazard is presented except in regions near the upper parts of these atmospheres. Also, the Jupiter magnetic field appears to be intense enough and extensive enough to provide extremely strong shielding from cosmic rays and solar flare particles over large regions of the planet.

5. Cosmic Rays in the Outer Solar System

There exist no direct measurements of cosmic rays in the region outside the earth's orbit. Our sources of information about such cosmic rays are as follows:

a) Meteorites

These are exposed to cosmic radiation in interplanetary space from the time that they are formed as entities not shielded effectively by surrounding matter. On approaching the earth they normally lose some of their outer layers during atmospheric entry, and of course in some cases fragmentation occurs. However, by measuring the isotopic changes within the meteorite caused by the cosmic ray bombardment, it is possible to estimate the time average of the cosmic ray intensity in the regions in which the meteorite moved. In particular, since meteorites appear to have high eccentric orbits, measured cosmic ray induced radioactivities of short life (weeks) must have been produced near the region of the earth's orbit, while those of long life (years) must have been produced over the entire orbit of the meteorite. By measuring the ratio of Ar^{37}/Ar^{39} (Ar^{37}:35 day half-life; Ar^{39}:325 year half-life) for a particular meteorite, Stoenner, et al.,[38,39] and Fireman, et al.,[40] were able to infer that the average cosmic ray flux near the earth's orbit, during the period of several weeks just before the meteorite fell, was within a factor of two of that averaged over the meteorite's orbit, which presumably extended out about as far as the asteroid belt at 2.8 AU, over the last few hundred years. While there are some weaknesses in generalizing this result, it is at least in the nature of a direct measurement. These results apply to cosmic rays integrated over the energy range $\sim$ 0.2-2 BeV.

b) High Energy Cosmic Rays

With some plausible assumptions it can be argued that the cosmic rays of energies of some few BeV and higher probably traverse the solar system with little change in intensity from the interstellar value. Thus the measured local values can be adopted as representative of the interplanetary high energy cosmic rays. This argument is supported strongly by the fact that the high energy cosmic rays are practically isotropic and constant in time, whereas the modulating magnetic fields in interplanetary space fluctuate with the solar cycle.

c) Theoretical Estimates of the Intensity of Low Energy Cosmic Rays

As mentioned in the Introduction, if we knew (i) the interstellar cosmic ray spectrum J_{IS} in detail, and (ii) the interplanetary magnetic field as a function of time t and positron r in the solar system, then we could calculate the modulation of J_{IS} to find J_{IP} (i, E, r, t). In the following, we make gross approximations to this calculation for particles with rigidities less than 2BV.

Interstellar low energy cosmic rays must be produced in at least two ways:

(i) Injection from stable and unstable stars. We now have direct information about the rate of emission of solar high energy particles for the period 1956-1961. From Malitson and Webber's[41] summary in the Solar Proton Manual, we can estimate that over a solar cycle the average particle emission by the sun is at the rate $\sim 10^{29}$ sec^{-1} (T > 30 MeV), $\sim 10^{28}$ sec^{-1} (T > 100 MeV). If all 10^{11}

stars in the galaxy injected particles at the solar rate, the total stellar injection rate would be equivalent to injection in the region of the galactic plane at a rate of $\sim 10^{-26}$ cm^{-3} sec^{-1} (> 30 MeV), $\sim 10^{-27}$ cm^{-3} sec^{-1} (> 100 MeV). Of course, since there is an extremely wide range of stellar types (including supernovae), and probably of particle injection rates, such estimates may be incorrect by orders of magnitude.

(ii) Production by collisions of high energy cosmic rays with the interstellar gas. Ferentz and Milford[42] have used the estimated intensity of 1-30 BeV interstellar cosmic rays to calculate the production spectrum of recoil protons in the range 0-500 MeV. They find an integrated production rate of $\sim 10^{-26}$ cm^{-3} sec^{-1}, which should be correct to an order of magnitude for the 1-30 BeV primaries considered (the contribution from $<$ 1 BeV primaries will be added later). By combining the production spectrum with the slowing lifetimes[43] of protons in the interstellar gas, the intensity of these 0-500 MeV protons is found to be ~ 0.1 cm^{-2} sec^{-1}, with the spectrum shown in Fig. 12.

It is possible that other processes, such as acceleration by interstellar magnetic fields, may contribute significantly to the production of low energy cosmic rays. Hatanaka, et al.,[45] have hypothesized a very high intensity of low energy cosmic rays in order to explain the heating of interstellar gas clouds, but at present there is no compelling reason to accept such high values.

As a result of the above discussion of the production of low energy interstellar cosmic rays, we see that we do not have enough information yet about the low energy particles bombarding the outer regions of the interplanetary magnetic fields. Turning now to the motion of these interstellar cosmic rays in the interplanetary magnetic field, we find that the information about the field, from the modulation[12] of 0.1-10 BeV solar and galactic cosmic rays observed at the earth, and from measurements of the field itself near the earth's orbit,[11,23] is not sufficient to uniquely define the field away from the earth's orbit. However, it is possible to set up a simple interplanetary magnetic field model, and then calculate the modulation as follows.

For simplicity, McCoyd and Milford[46] adopt Parker's[47] diffusion model in which locally ordered regions of the magnetic field act as scattering centers. If these scattering centers move outward with the solar wind a steady state is reached with the cosmic ray intensity in the solar system depressed below the value in interstellar space. The solar wind is assumed to be radial and constant out to the position of the shock transition between the interplanetary and interstellar plasmas. Following Parker,[48] and Axford, Dessler, and Gottlieb,[49] we adopt the size ℓ of the scattering centers as $\ell = \ell_0(r)^{2/3}$ and the average magnetic field B within a scattering center as $B = B_0/r$, where r is the distance from the sun. We calculate the modulation produced by this spherically symmetrical field on the assumption that it extends out to a distance of 50 AU. The shock region will affect the lowest energy particles, but apart from this, the major part of the modulation occurs, for example, inside the orbit of Jupiter (5 AU) for protons with $T < 200$ MeV, so that it does not matter too much on this model where the shock region is, provided that it is not within 3 or 4 AU from the Sun. In a paper just published, Morris, Clark and Wilson[51] conclude that the interstellar magnetic field is probably much smaller than suggested by earlier results. This would move the shock region further out in the solar system.

Adopting values corresponding to near solar-cycle maximum $B_0 = 3 \times 10^{-5}$ gauss AU, $\ell_0 = 10^{-2}$ AU$^{1/3}$, and $v = 500$ km/sec,[11,23,50] we find the modulation factor J(rAU)/J(50 AU) as a function of particle energy and position in the solar system;[46] the results for protons and iron nuclei are presented in Figs. 13 and 14. It can be seen that, if this model is correct even within orders of magnitude, no interstellar protons with energies less than 10 or 20 MeV would penetrate into the solar system as far as the orbit of Jupiter. Also, on this model, iron nuclei are modulated more than protons of the same rigidity, but less than protons of the same energy per nucleon.

6. Radiation Dose Rates from Cosmic Rays in the Solar System

In the previous sections we have summarized the known and estimated charge and energy spectra of cosmic rays in the solar system. The corresponding approximate dose rates can be calculated from various conversion formulas:[52-54] The physical dose in rep or rad is multiplied by the relative biological effectiveness (RBE) to give the dose equivalent in rems. The RBE factors are reasonably well known for protons, light nuclei, neutrons, electrons, and X- and gamma-rays, but there is still considerable uncertainty about the effects of heavy nuclei. Thus, while the contribution of heavy primaries to the total ionization per gm per second is only about 5%, their actual ionizing tracks when they occur have physical doses of the order of 10^4 roentgen in their cores. Since the bulk of this ionization occurs within a column only some few microns thick, i.e., comparable in size to living cells, it is probable that the occasional lethal hit on irreplaceable cells is much more important than the over-all ionizing effects from the bulk of the cosmic ray intensity. For this reason, until the radiation effects of the heavy primaries are better understood, their radiation effect is quoted in hits cm^{-3} sec^{-1}.

We note that the present permissible whole body doses for occupational workers (whole population) are 5(0.2) rem/year, 0.1(0.003) rem/week, respectively.[52] These values do not include doses from medical and background exposure (latter is our prime concern here). In practice, in exploratory missions there will be more consideration given to the total accumulated dose, which should not come to more than 100-200 rems if serious radiation sickness is to be avoided. It is interesting to note that the dose rate due to cosmic rays a) at sea level is ~ 0.001 rem/week b) at supersonic transport altitudes (20 km) is ~ 0.2 rem/week.[55]

For cosmic rays outside the strong field part of the geomagnetic cavity, the dose rate from the over-all ionization produced in an unshielded human being is $\sim$ 0.5-1 rem/week,[54] and this rate diminishes as the point considered moves into the denser parts of the geomagnetic field.

It will be recalled (Section 2) that at points just outside the atmosphere the albedo flux of charged particles and neutrons becomes appreciable. The dose from the cosmic ray plus secondary charged particles there is about the same as the free space dose, and from the albedo neutrons there it is $\sim$ 0.1 rem/week. The dose rates near the moon's surface are about the same for the charged particles and neutrons as for the extra-atmospheric case. At the surface of Mars the dose rate[35,36] is possibly $\sim$ 0.2 rem/week.

In regions far out in the solar system, Section 5 suggests that we might find an appreciable intensity of cosmic rays in the 0-300 MeV region, which would make the total unshielded dose rate > 1 rem/week. However, these lower energy cosmic rays can be usefully reduced by reasonable size shields ($\sim$ 20 gm cm^{-2} say). In addition, these thin shields can absorb the heavy nuclei or convert them rather efficiently to lighter nuclei of lesser danger. On the other hand, quite thick shielding ($\sim$ 200 gm cm^{-2}) is required to significantly reduce the intensity and dose rate of average cosmic rays (thinner shielding tends to produce harmful secondaries as well as slowing some of the primaries to energies at which they give larger dose rates).

As far as damage from heavy primaries is concerned, Yagoda, et al.,[56] and Curtis and Smith,[57,58] give some experimental evidence that these primaries may not constitute as large a hazard as had been thought, but much more work is required before we shall know the exact radiation effects of these heavy primaries.

In summary, the known hazard presented by cosmic rays is appreciable only for long term space missions, such as one or two year trips to planets, or possibly for bases on the Moon or Mars, when unshielded total doses of ~ 100 rem may be accumulated. Possible unknown hazards might arise from heavy nuclei in the inner solar system, or, in future missions, from high intensities of light or heavy nuclei in the outer solar system; but shielding should not be too difficult for these cases (see recent articles on shielding[54,59] and the calculation of radiation doses on space missions).[60]

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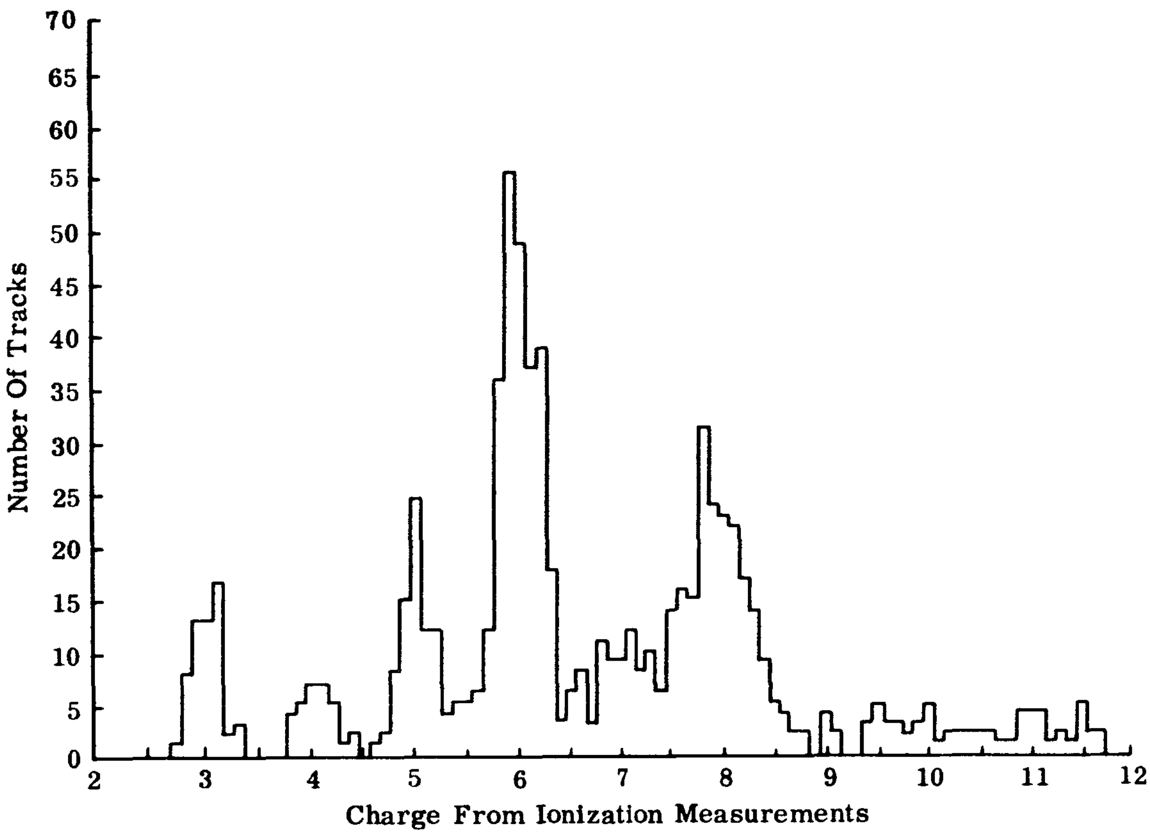

Fig. 1 Frequency distribution of nuclear charge for 746 cosmic ray tracks with $3 \leq Z \leq 11$. It is evident that good resolution was achieved between the light elements ($Z \leq 5$), and those with $Z \leq 6$. From Shapiro, Hildebrand, O'Dell, Silberberg, and Stiller[5].

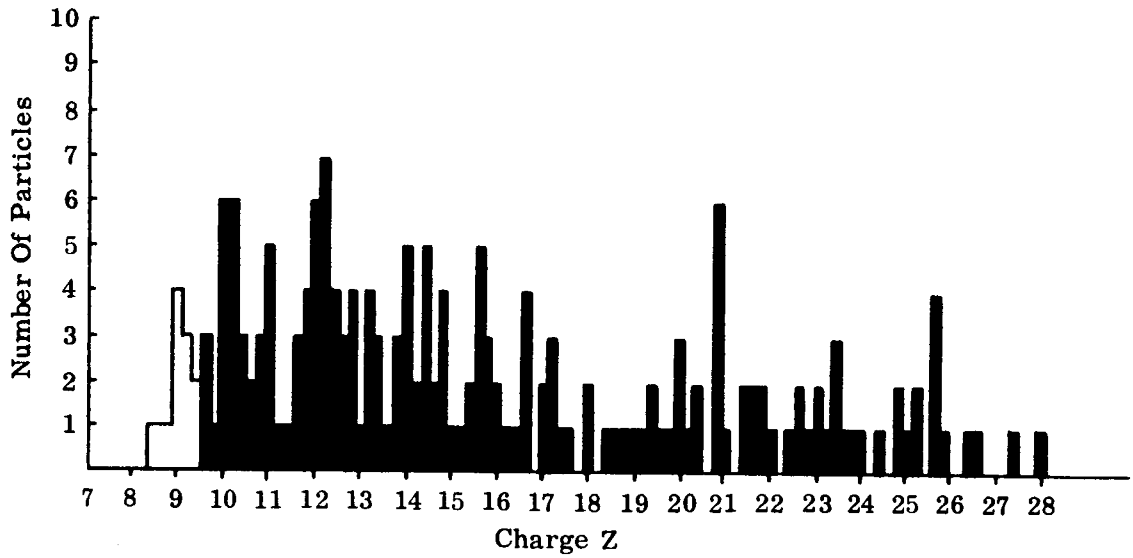

Fig. 2 Charge spectrum of 178 cosmic ray heavy nuclei with $Z \geq 10$. From Neelakantan and Shukla[6].

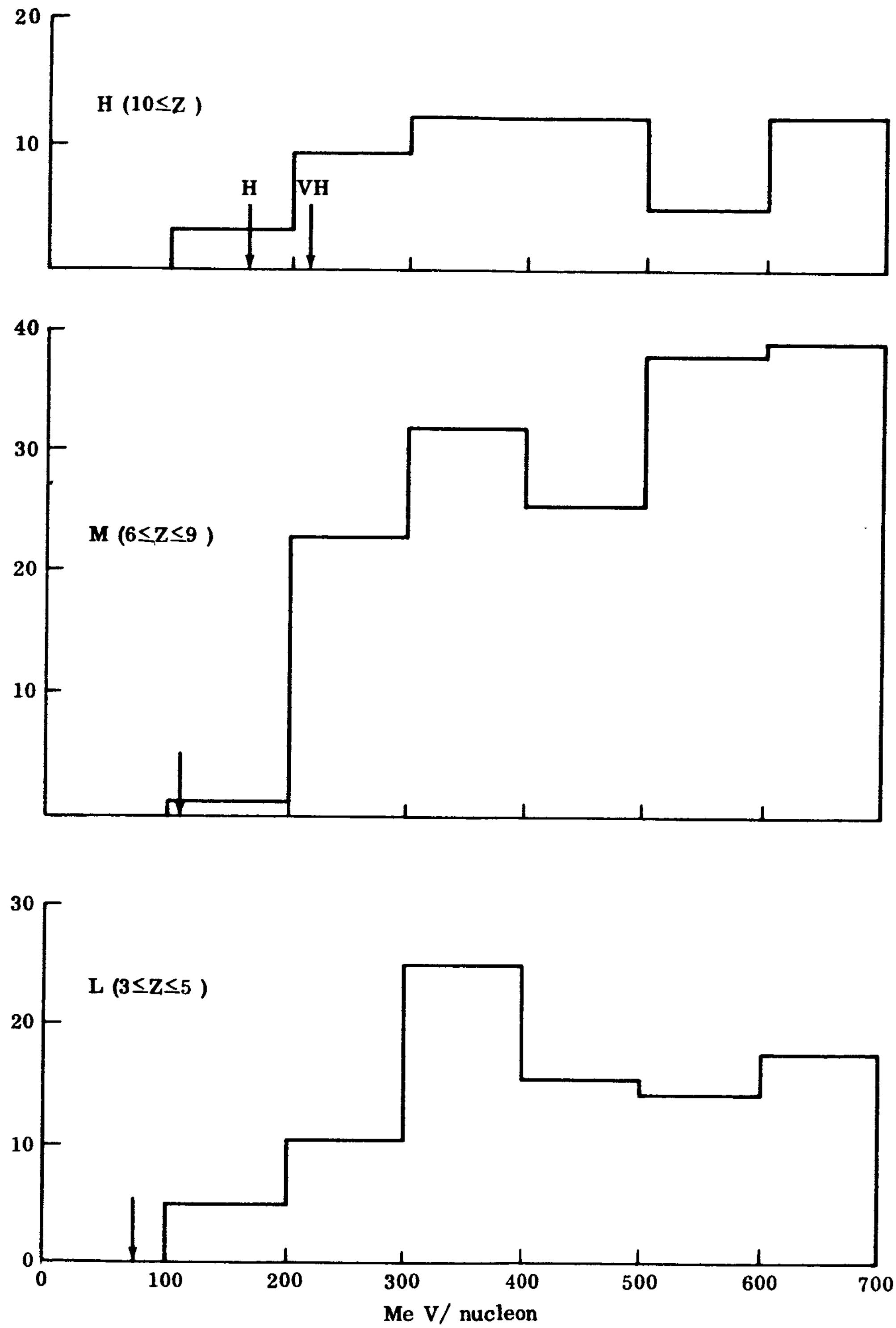

Fig. 3 Energy spectrum of L, M, and H nuclei at the top of the atmosphere. Arrows: air cutoff. Ordinate: number of particles in 100-Mev interval. From Koshiba, Lohrmann, Aizu, and Tamai[7].

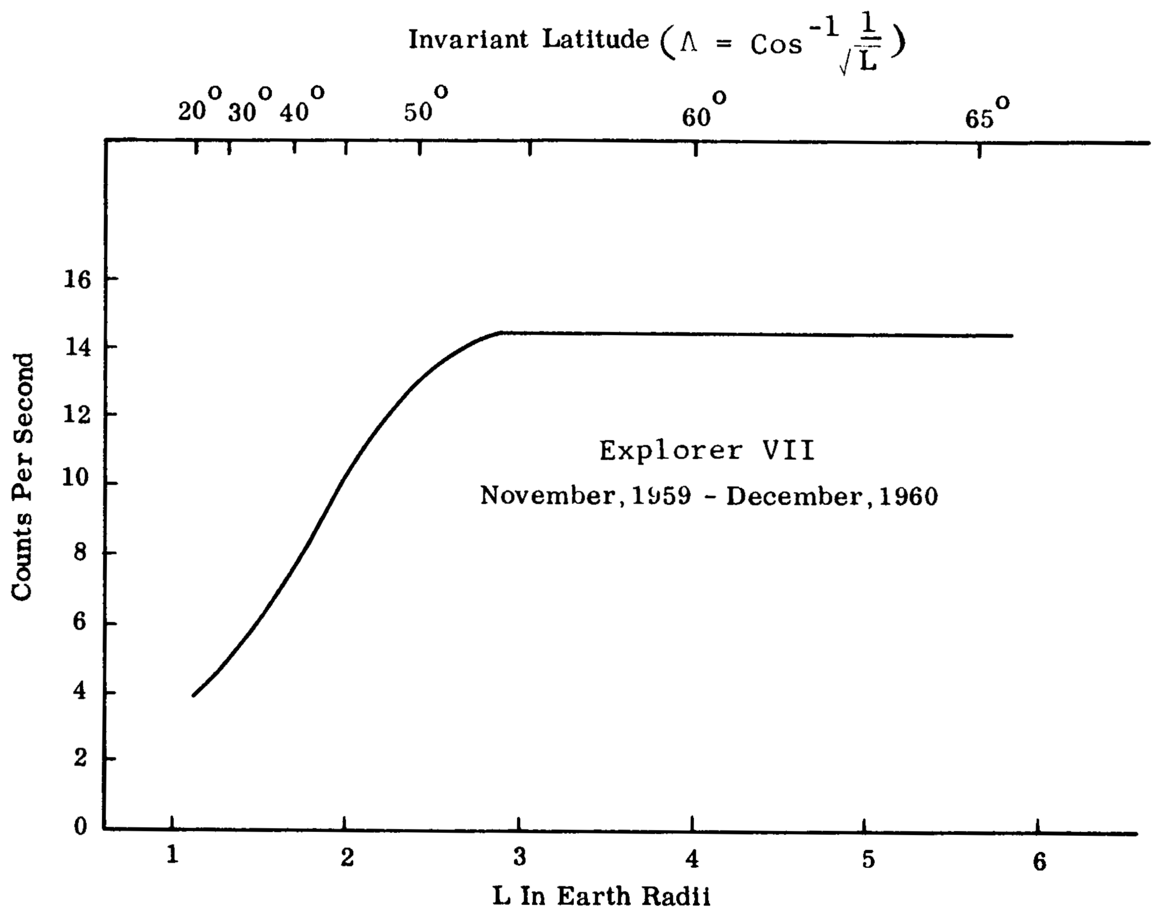

Fig. 4 Dependence of average charged particle counting rates on L. Adapted from Lin, Venkatesan and Van Allen[13].

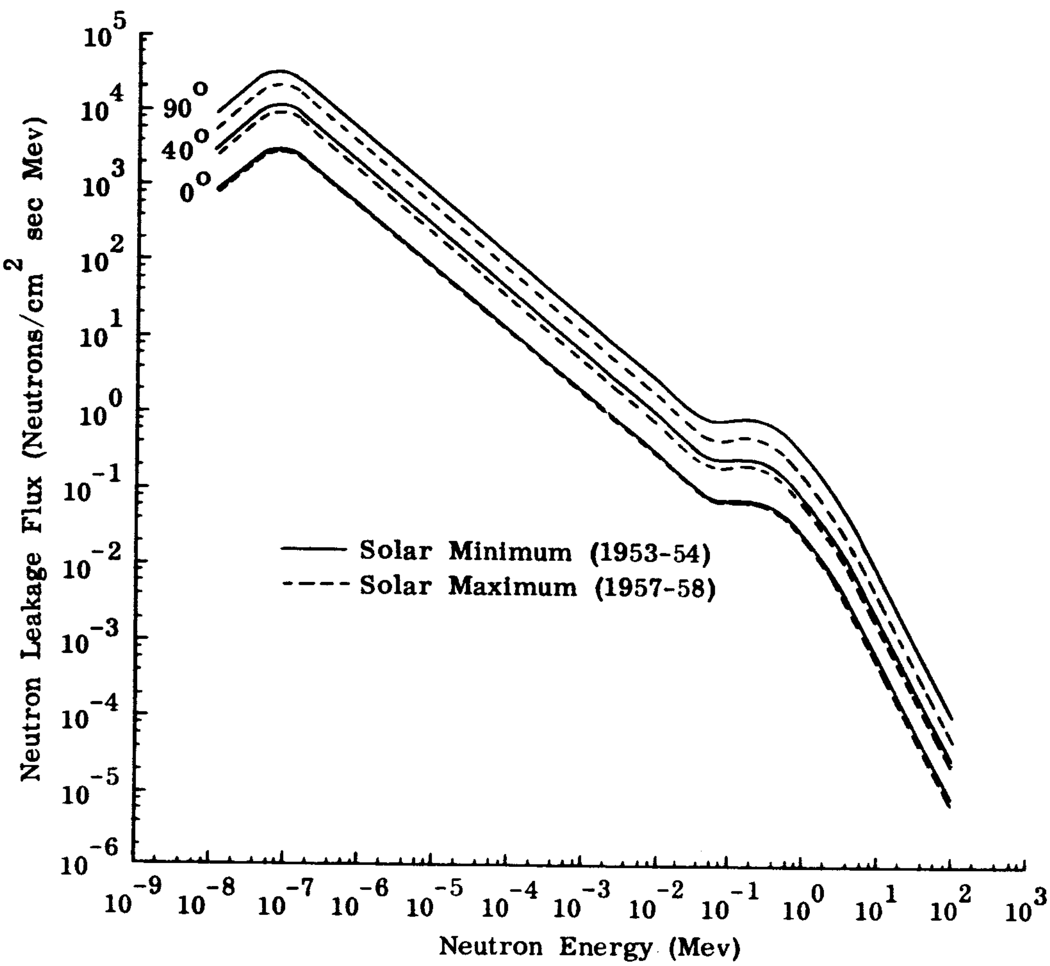

Fig. 5 The cosmic-ray neutron leakage flux spectrum at 0°, 40°, and 90° geomagnetic latitude for solar minimum and solar maximum. The spectral shape above 10 Mev is from the measurements of Hess et al. (1959). From Lingenfelter[17].

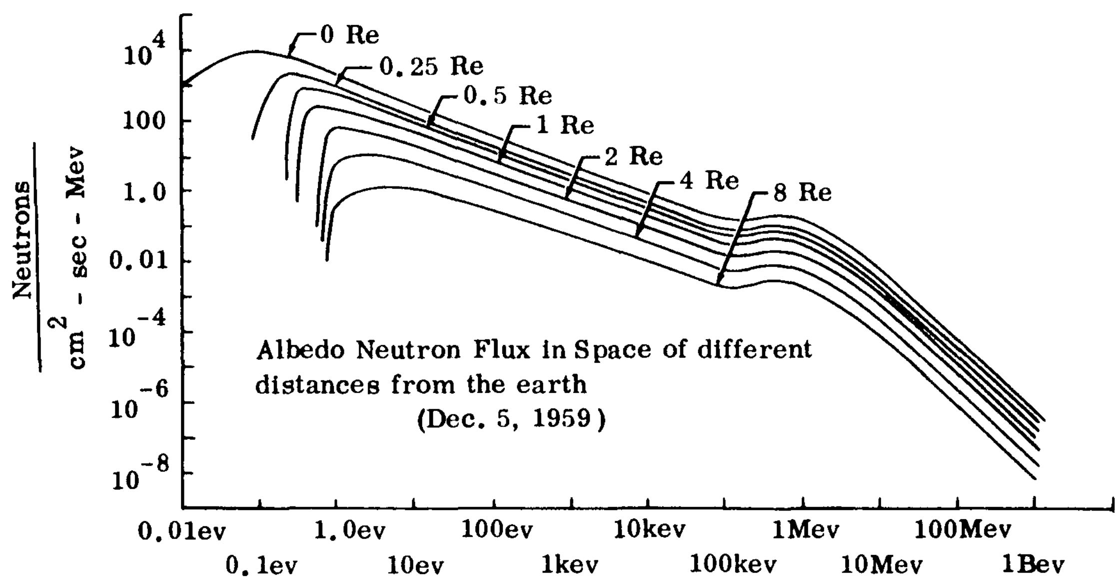

Fig. 6 Neutron energy spectra in space at different distances from the earth above the geomagnetic equator. Distance unit is radius of the earth (Re). The 0 Re curve is for the top of the atmosphere, which is roughly 100 km. From Hess, Canfield and Lingenfelter[18].

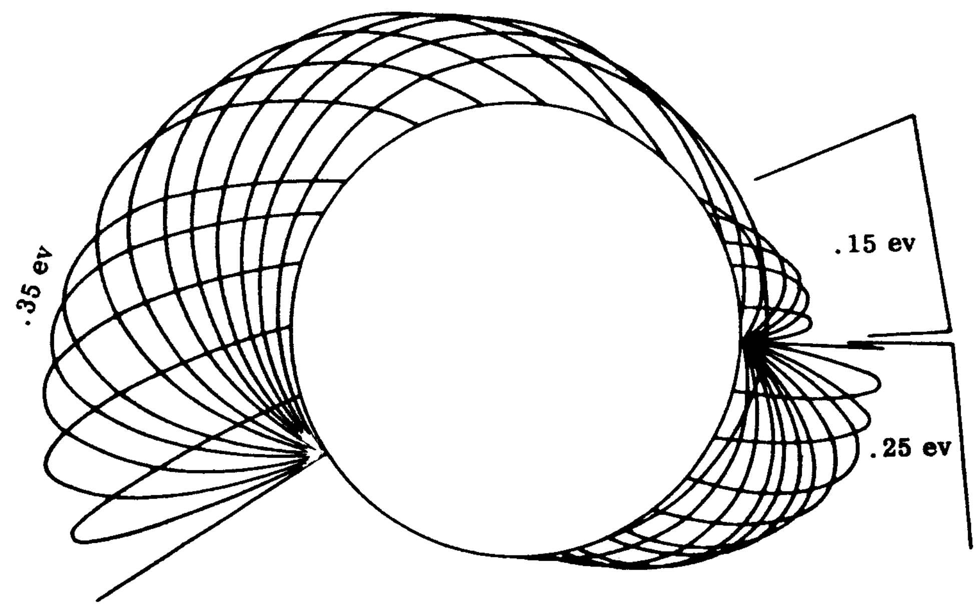

Fig. 7 Orbits of neutrons gravitationally trapped in space near the earth. Three sets of orbits are shown for neutrons of three different energies: E_n = 0.35, 0.25, and 0.15 ev. Adapted from Hess, Canfield and Lingenfelter[13].

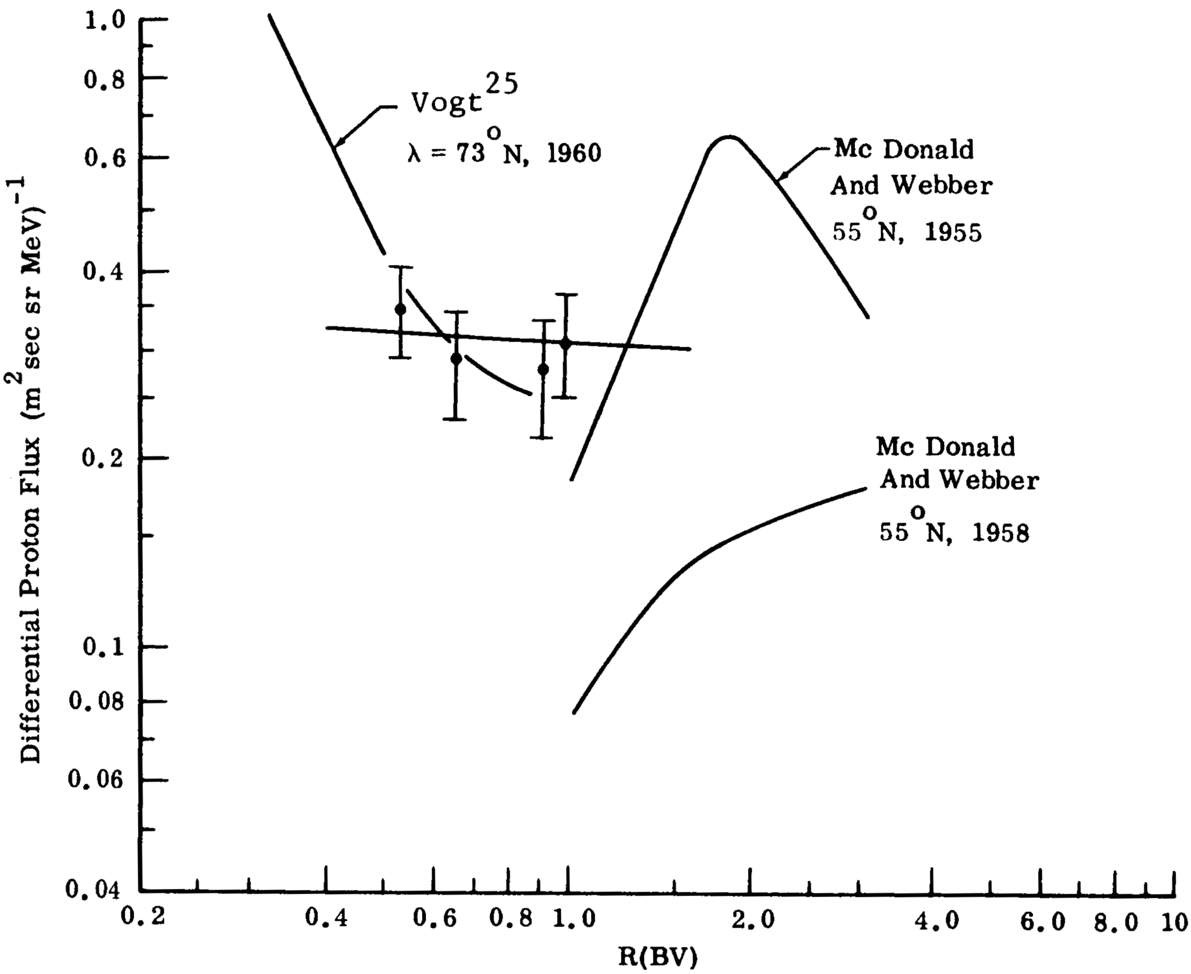

Fig. 8 Low energy primary cosmic ray spectrum measured by Explorer XII. The points with bars, and the figure, are from Bryant, Cline, Desai and McDonald[24].

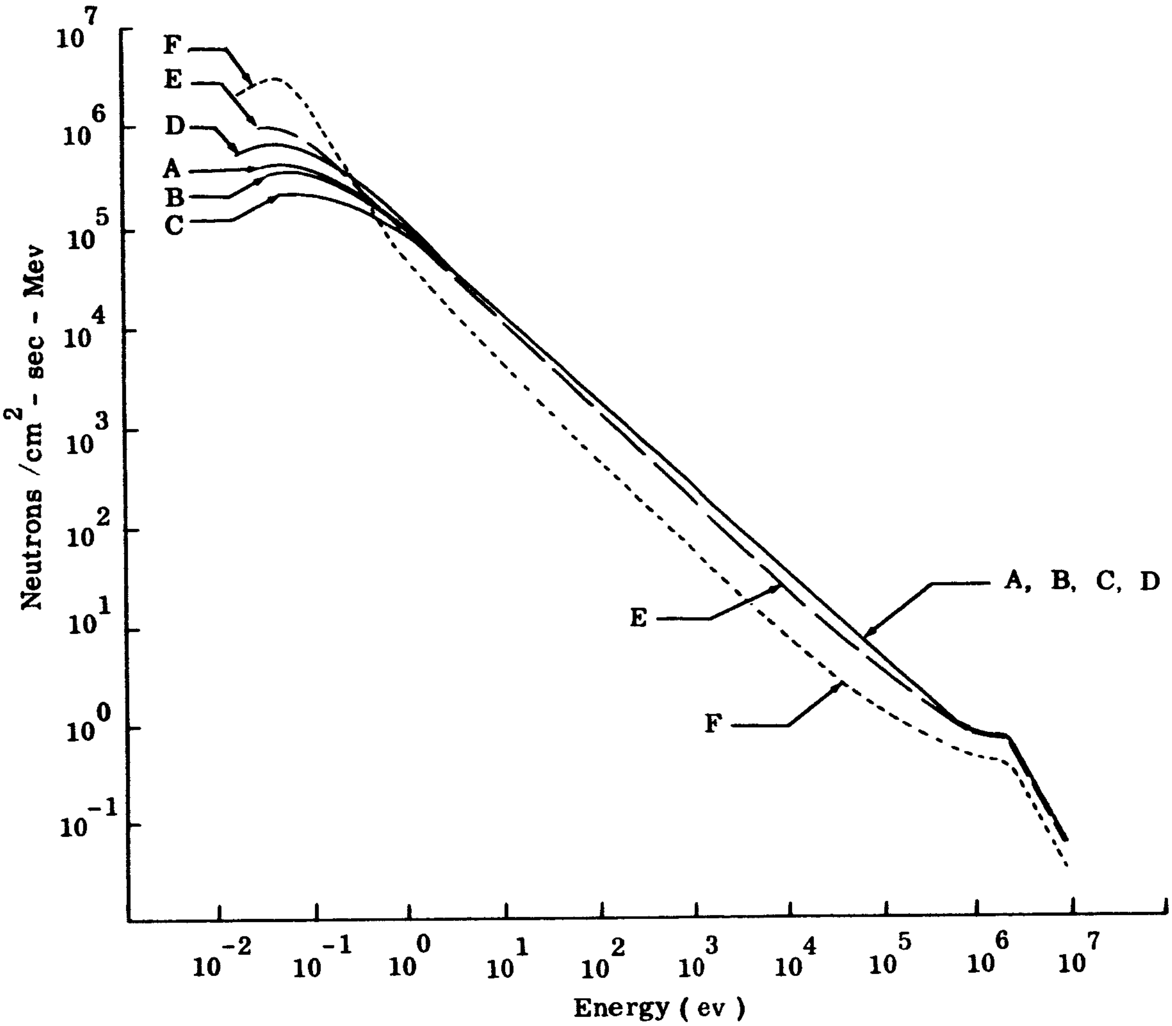

Fig. 9 The calculated neutron equilibrium leakage spectrum for the lunar surface for compositions A, chondritic material; B, chondritic material with a 10 per cent increase in the total 1/v capture cross section; C, with a 50 per cent increase in 1/v capture; D, with a 35 per cent decrease in 1/v capture; E, chondritic material with 0.1 H/Si atom; and F, with 1.0 H/Si atom. From Lingenfelter, Canfield and Hess[27].

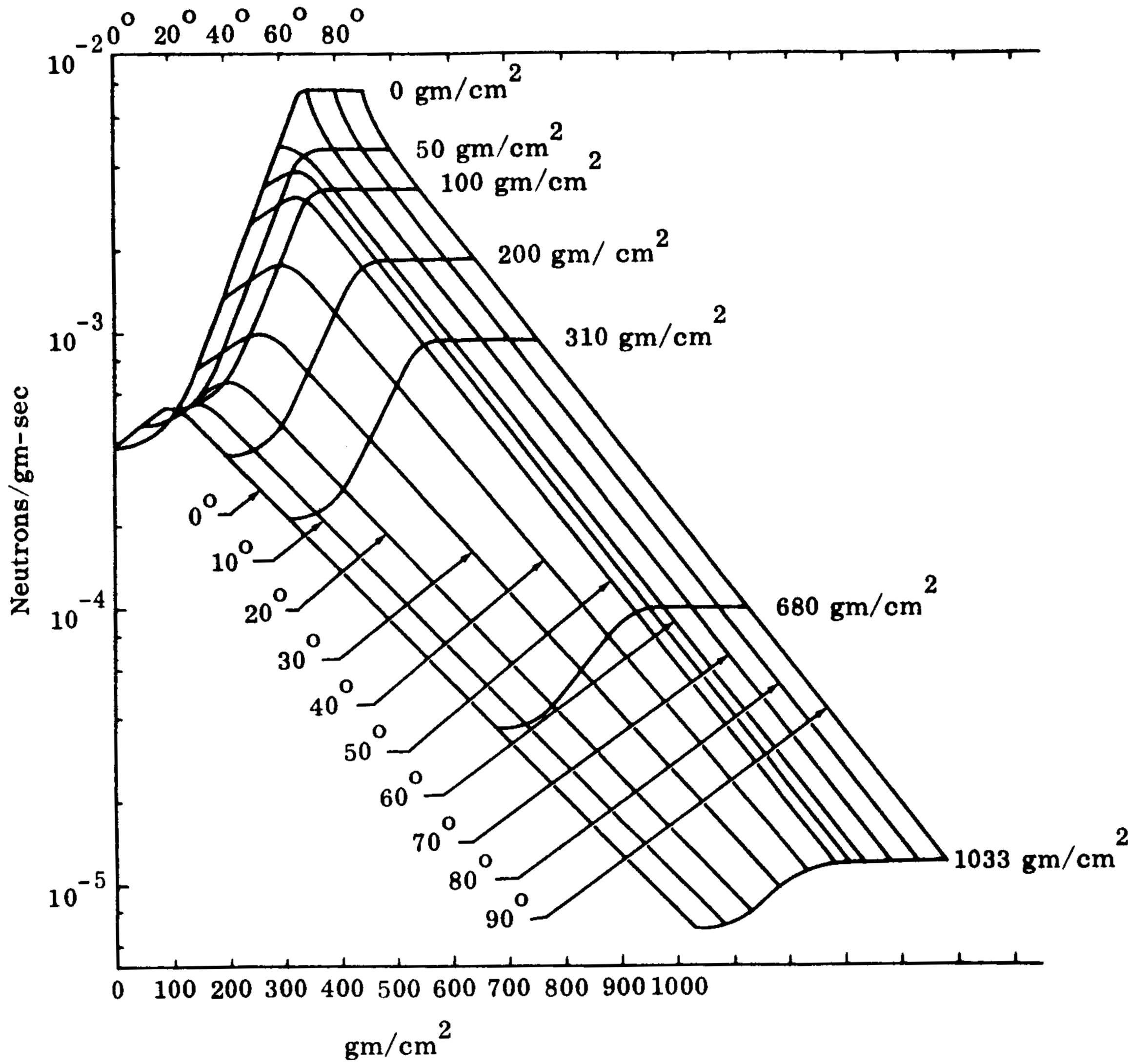

Fig. 10 The solar minimum cosmic-ray neutron production rate in neutrons/g sec as a function of altitude, g/cm^2, and geomagnetic latitude, normalized to a total production rate of one neutron per square centimeter column of air per second at the geomagnetic pole. From Lingenfelter[17].

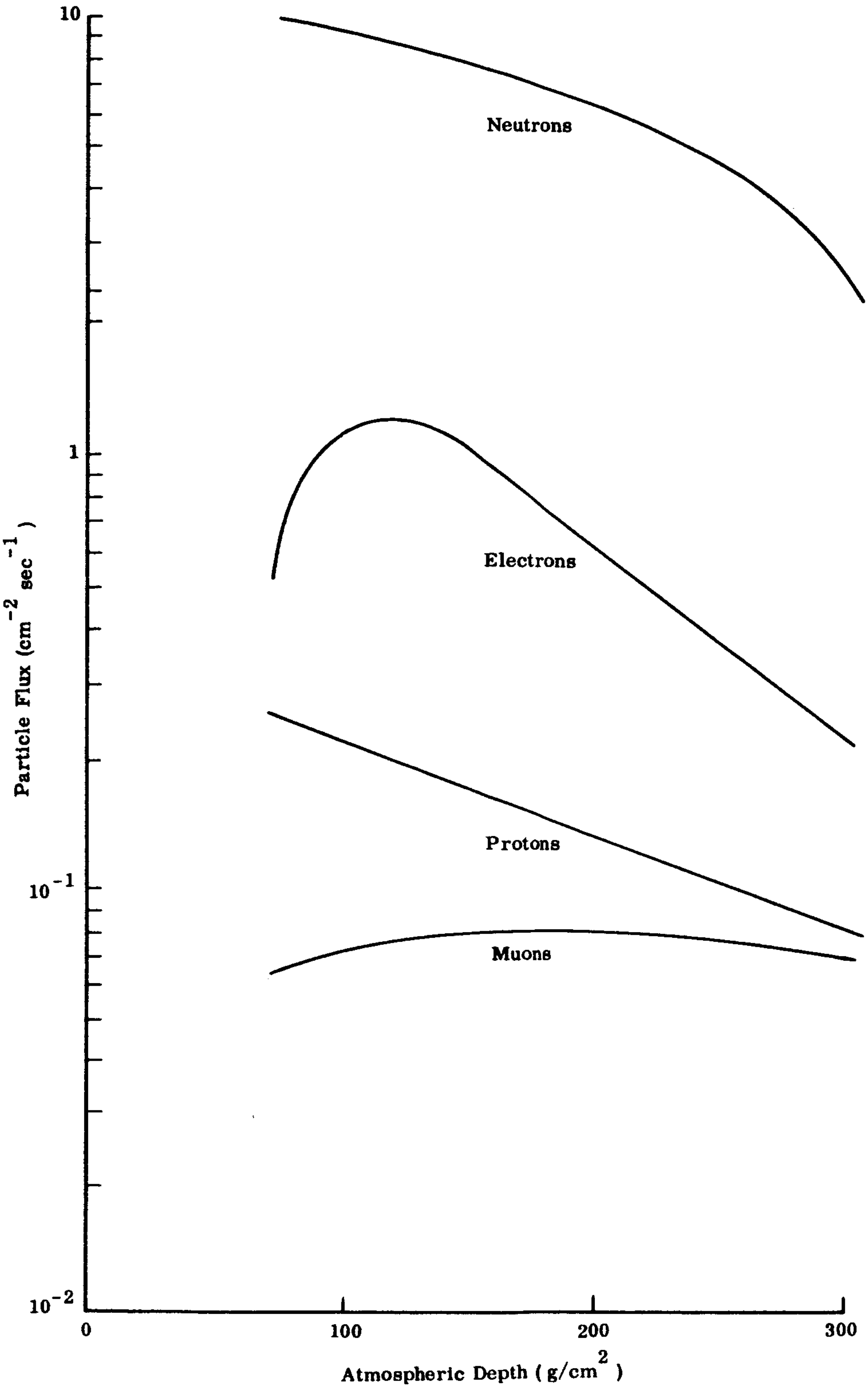

Fig. 11 Particle fluxes produced by cosmic rays as a function of depth in the Martian atmosphere. From Fink and Milford[36].

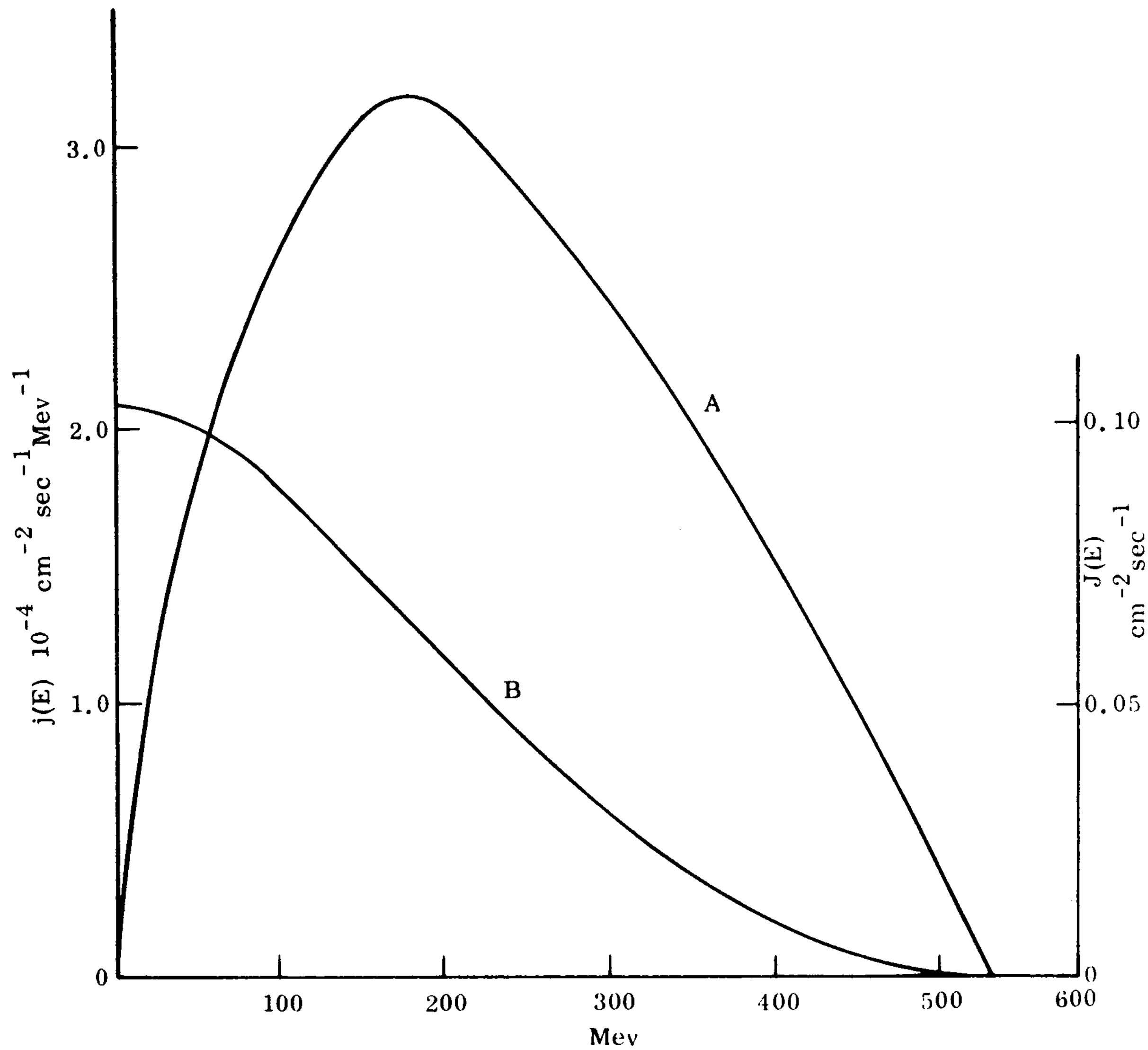

Fig. 12 A: Differential spectrum of low energy cosmic rays (cm^{-2} sec^{-1} MeV^{-1})
B: Integral spectrum of low energy cosmic rays (cm^{-2} sec^{-1}).
From Ferentz and Milford[42].

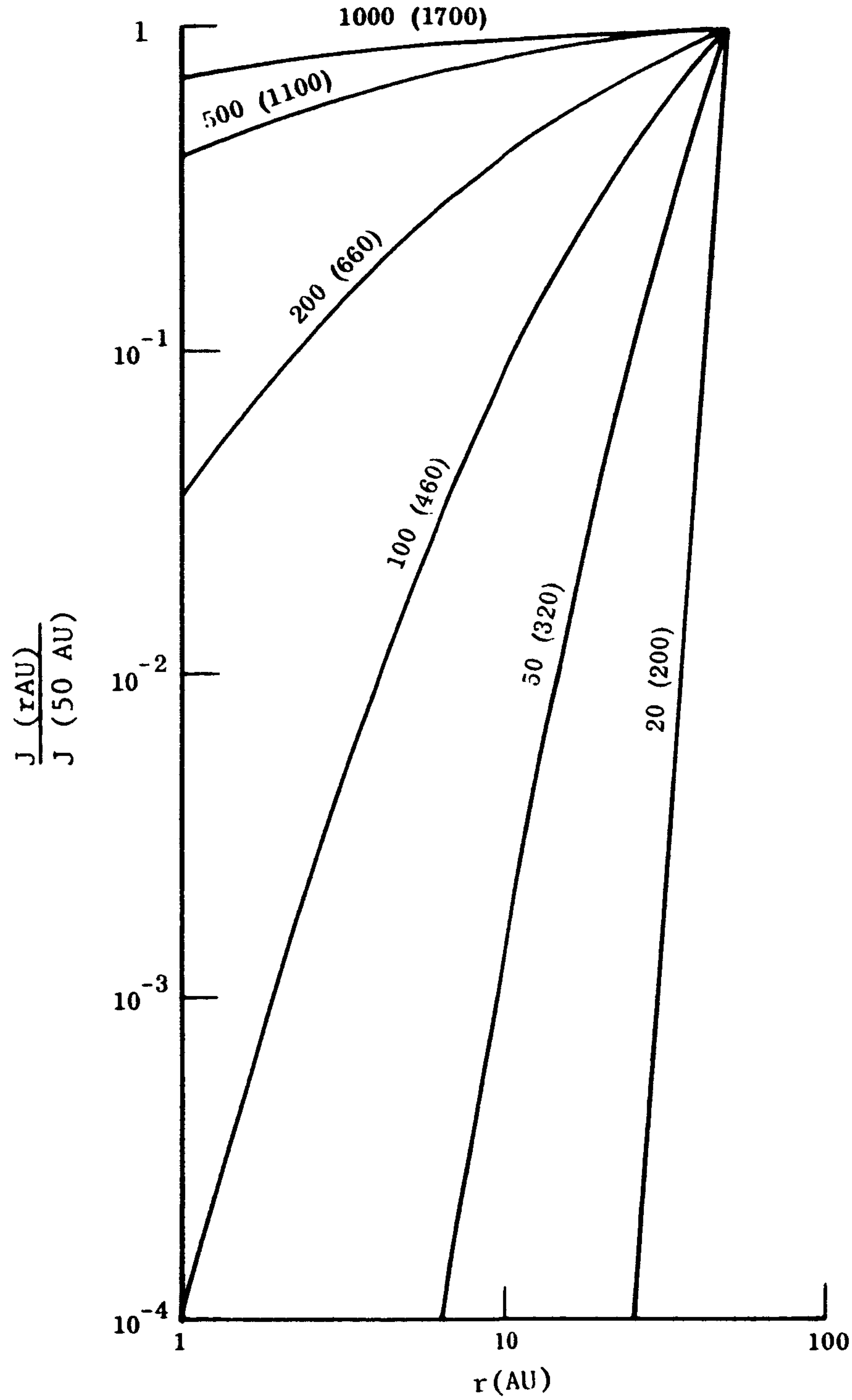

Fig. 13 Modulation of galactic cosmic ray protons calculated by means of a simple model of the interplanetary magnetic field. The curves are labelled T(R) where T is the kinetic energy/nucleon in MeV, R the rigidity in MV. From McCoyd and Milford[46].

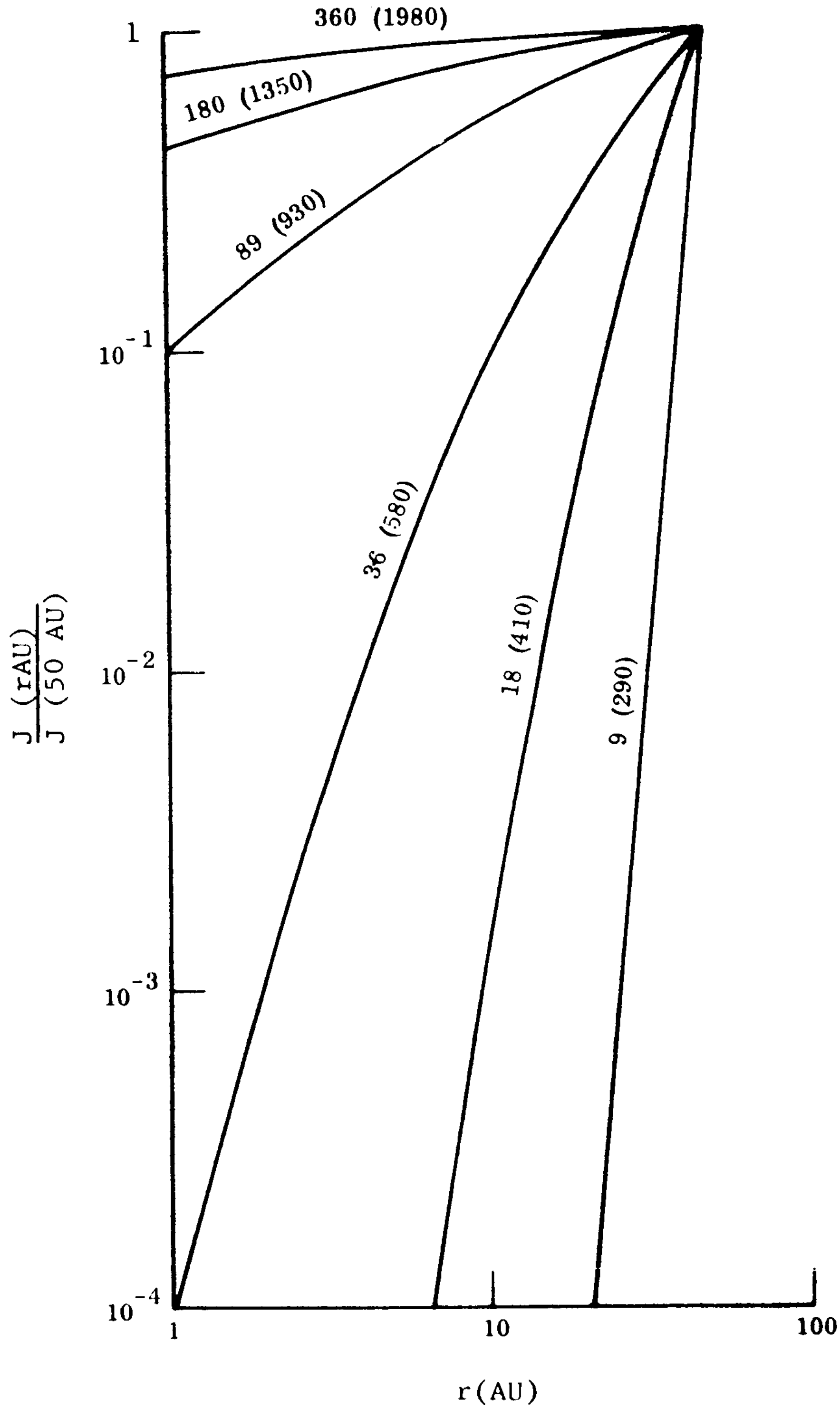

Fig. 14 Modulation of galactic cosmic ray iron nuclei calculated by means of a simple model of the interplanetary magnetic field. The curves are labelled as in Fig. 13. From McCoyd and Milford[46].

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